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COVER SHEET FOR TECHNICAL MEMORANDUM

TITLE- The Effect of the Meteoroid Environment on a Coated Columbium Radiative Heat Shield for a Space Shuttle

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ABSTRACT

The meteoroid environment in space may present significant hazards to a Space Shuttle heat shield particularly if it is composed of coated refractory metals such as columbium. These hazards may not only jeopardize mission success but also affect post flight inspection and repair operations prior to Space Shuttle reuse. This memorandum presents a preliminary assessment of the risk of heat shield meteoroid damage due to: 1) puncture of the metallic heat shield, and 2) pitting of the heat shield coating.

Radiative heat shields, as currently designed, will not satisfy a meteoroid design probability of greater than 0.9 that no punctures will occur in a single 3-day mission. If a no-puncture probability of 0.999 is adopted, the concept of a radiative metallic heat shield does not appear very attractive due to large weight penalties. If a puncture can be allowed, current heat shield weight estimates are not significantly affected.

For a typical 3,000 ft^2 heat shield, less that 100 pits per mission should occur through the protective coating, with a more likely number of about 20. The corresponding damaged coating surface areas are 0.022 in^2 and 0.004 in^2 respectively.

Acceptable values of damaged coating surface areas remain to be established. However, tests indicate that damaged coating areas can be visually identified. This could facilitate post flight inspections. Relaxation of meteoroid design criteria, combined with some sacrifice of payload capability can reduce the frequency of post flight operations or increase mission durations.

To adequately assess the risk of critical heat shield meteoroid damage, more laboratory testing should be performed to determine the effects of high speed hot gas impingement, similar to the reentry environment, against punctured or pitted specimens.

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SUBJECT: The Effect of the Meteoroid Environment on a Coated Columbium Radiative Heat Shield for a Space Shuttle

DATE: April 17, 1970

FROM: J. C. Burford
C. E. Johnson
C. C. Ong

TM-1012-1

TECHNICAL MEMORANDUM

1.0 INTRODUCTION

The meteoroid environment in space may present significant hazards to a Space Shuttle heat shield particularly if it is composed of coated refractory metals such as columbium. These hazards can jeopardize mission success and affect post flight inspection and repair operations prior to space shuttle reuse.

If a sufficiently large meteoroid strikes the heat shield the protective coating will be penetrated, thereby exposing the columbium substrate to the surrounding oxygen during reentry. This could lead to excessive columbium oxidation resulting in a loss of heat shield structural strength. In addition, if the total heat shield wall is punctured, internal Space Shuttle systems could be endangered by hypervelocity particle fragmentation and subsequent heat leakage.

This memorandum gives a preliminary assessment of the risk of critical meteoroid damage by estimating expected puncture rates of both the protective coating and the total metallic heat shield. Cumulative heat shield coating surface areas damaged by impacting meteoroids are also estimated. Heat shield hazards and meteoroid design criteria implications are discussed.

2.0 STUDY APPROACH

A typical Space Shuttle configuration is shown in Figure 1 for which a radiative metallic heat shield surface area of 3000 ft^2 is assumed. The Space Shuttle is considered to be orbiting the earth in a random vehicle orientation at an average altitude of 210 nm. The mission duration is 3 days.

Meteoroid penetration of the radiative heat shield is dependent on Space Shuttle vehicle orientation relative to the earth. This dependency exists due to the meteoroid shielding characteristics of the earth and the location of the radiative heat shield on the base of the vehicle (see Figure 1).

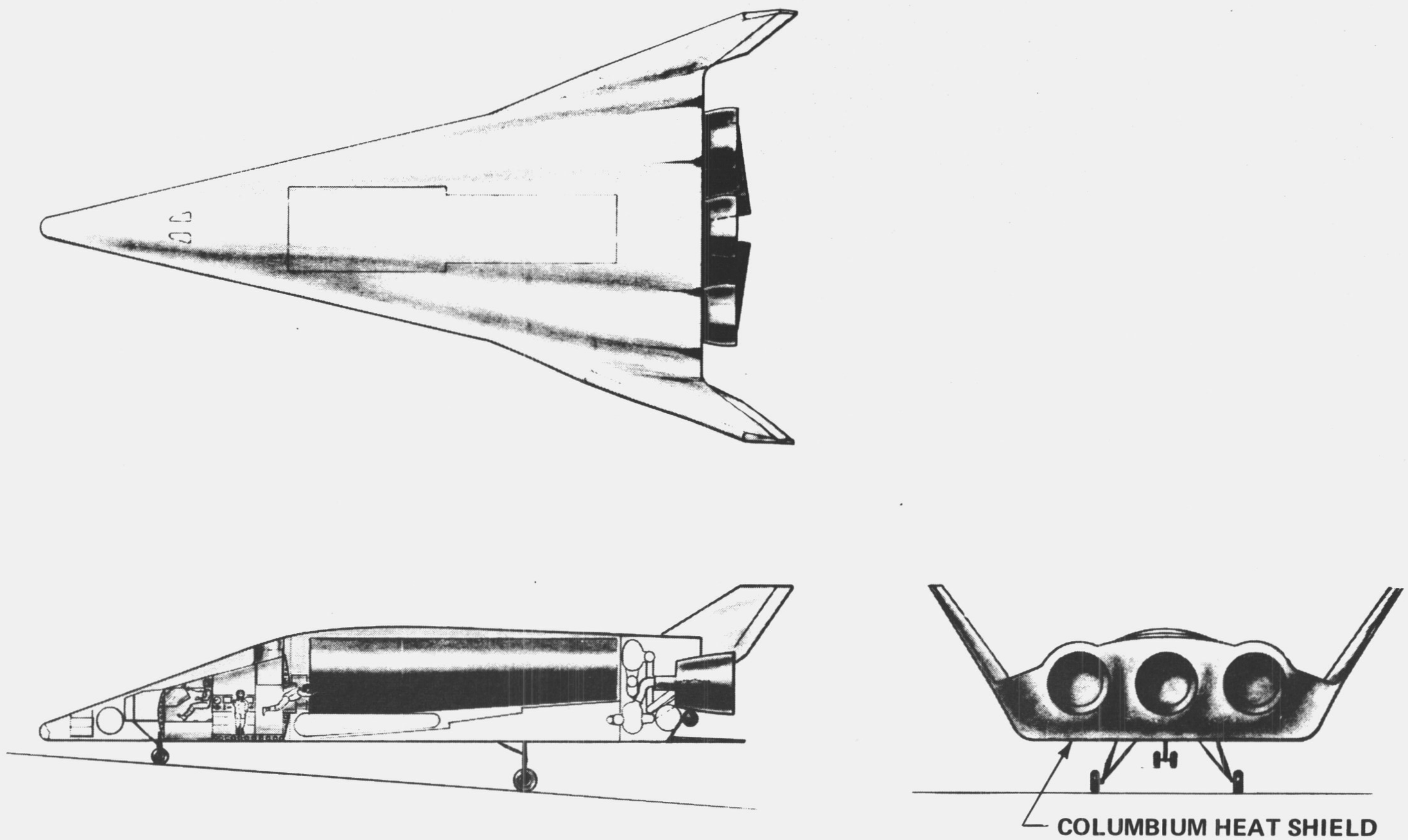

FIGURE 1 - TYPICAL SPACE SHUTTLE ORBITER CONFIGURATION

If the Space Shuttle were to fly only in a heat-shield-down orientation (facing the earth), the earth would provide protection against those meteoroids that would otherwise strike if the earth were not in the way. Very little additional meteoroid protection, if any, would therefore be required. However, this mission mode is considered to be overly restrictive for purposes of advanced planning. For this reason, a random Space Shuttle vehicle orientation is considered with a uniform meteoroid environment which accounts for the meteoroid shielding characteristics of the earth.

A cross sectional view of a radiative heat shield is shown in Figure 2 which is representative of current preliminary Space Shuttle design (References 1 and 2). The dimensions cited relate to minimum gage estimates and requirements for heating and aerodynamic loading. They are representative of a heat shield that is not designed by the meteoroid environment. The heat shield base metal is columbium alloy Cb 752 with a protective coating of Sylvania R512E System composed of SL-20Cr-20Fe and laquer. The coating has an equivalent surface Brinell Hardness Number (BHN) between 780 and 1050.*

A theoretical approach is used to determine the risk of critical meteoroid damage in which Apollo design criteria are used (See Appendix A). The cislunar meteoroid environment cited in the Natural Environment and Physical Standards for the Apollo and the Apollo Applications Program (NEPSAP) (Reference 4) is employed along with the North American-Rockwell penetration equation (Reference 5), which was adopted for Apollo. To assess the validity of this approach, a comparison is made with in-flight meteoroid penetration data and Whipple predictions (See Appendix B).

It is not desirable to apply experimental data directly because:

- the extreme hardness of the heat shield coating (780<BHN>1050) is not comparable with any materials used during flight measurements (BHN$\lesssim$300),

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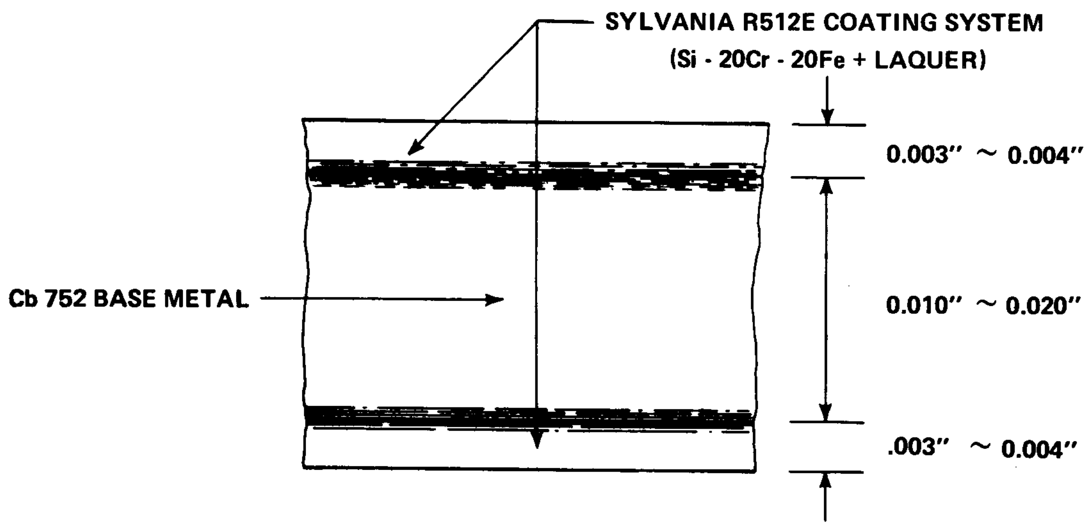
* Hardness numbers of Rockwell C=70 and Microhardness = 1050 were furnished by S. Priceman of Sylvania Electric Product Inc. as being representative of coating hardness, per a telephone call with C. C. Ong on September 3, 1969. These hardness numbers are equivalent to BHN^s of 780 and 1050 respectively (Reference 3).



A–A

CROSS SECTION OF COLUMBIUM HEAT SHIELD

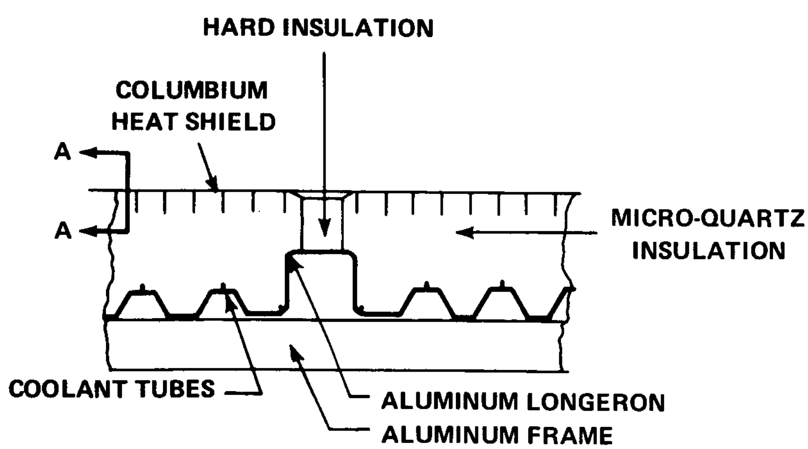


FIGURE 2 - COATED COLUMBIUM RADIATIVE HEAT SHIELD WITH SUPPORTING STRUCTURE

- the coating is between approximately 1/5 and 1/9 of the total heat shield thickness and it is assumed that the mechanics of coating penetration are closer to those of semi-infinite penetration than those of thin-sheet penetration which characterize in-flight satellite experiments, and

- an understanding of the relationship between coating thickness and the probability of a given number of penetrations ocurring is desired. Such a relation is essential in tradeoff studies concerning meteoroid design criteria and the maximum allowable vehicle thermal environment.

3.0 UNCERTAINTIES

3.1 General

Uncertainties exist in predicting heat shield meteoroid resistance because of: 1) a lack of data to adequately characterize the meteoroid environment, and 2) an incomplete understanding of hypervelocity penetration mechanics.

Factors affecting environmental uncertainty include the meteoroid flux, particle velocity and particle density. The maximum uncertainty variation in required shielding weights for the near-earth environment is discussed in some detail in Reference 6. Environmental uncertainties are not considered in this analysis.

Uncertainty is associated with penetration mechanics because meteoroid penetration cannot adequately be simulated in tests since particles of expected meteoroid sizes and densities cannot be accelerated to sufficiently high velocities. Theories have not adequately correllated with tests performed with achievable velocities (Reference 7) so that extrapolation of semi-empirical data to expected velocities is uncertain.

3.2 Heat Shield Coating Penetration

Aerospace materials in general have Brinell Hardness Numbers of $\lesssim$ 300, whereas the heat shield coating has an equivalent Brinell Hardness Number between 780 and 1050. Because of this difference, a substantial amount of additional uncertainty exists in predicting coating penetration rates since penetration resistance varies with target hardness and it has been assumed that the North American-Rockwell penetration equation (written in terms of BHN) also applies in this extreme hardness range. Moreover, it has been assumed that this equation, which describes penetration into a semi-infinite, homogeneous and isotropic body, can be used to determine penetration rates into a heat shield which is actually a composite structure. Since the coating thickness is between 1/5 to 1/9 the thickness of the total metallic heat shield, the applicability of the semi-infinite characteristic of the penetration equation appears reasonable for preliminary calculations.

It is estimated that an uncertainty of ≈ 2 in coating thickness could be associated with extrapolation of the penetration equation into this extreme hardness range. That is, the thickness required to prevent more than n pits through the coating could be low by a factor of 2. The effect of this uncertainty is included in this memorandum for comparison purposes (An uncertainty of 1 infers that no uncertainty exists in the theoretical approach).

3.3 Total Heat Shield Penetration

The equivalent composite Brinell Hardness Number for the total heat shield (see page 6) falls in the hardness range of standard aerospace materials. Consequently the calculations should be more accurate for total heat shield penetration than for coating penetration.

4.0 HEAT SHIELD COATING PITTING* RATES

A firing process is involved in applying the heat shield coating to the refractory base metal. This process results in intermetallic diffusion between the coating and the base metal creating a gradual change of properties at the interface. (This blending effect is depicted in Figure 2). Therefore, for meteoroid calculations, the coating is assumed to be between 0.003 and 0.004 inches thick.

To provide generality in this study, coating thickness is treated as a variable with respect to the expected number of pits. Figure 3 shows the variation of required heat shield coating thickness with the number of expected pits assuming a BHN of 850. Two pairs of curves are shown, each pair corresponding to the probabilities of 0.5 and 0.999 that n pits or less will occur. (In other words, greater than n pits will occur in 5 out of 10 missions for a probability of 0.5, and in 1 out of 1000 missions for a probability of 0.999. Therefore, more risk is involved

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* A pit is defined as a meteoroid crater in the heat shield deep enough to completely penetrate the heat shield coating.

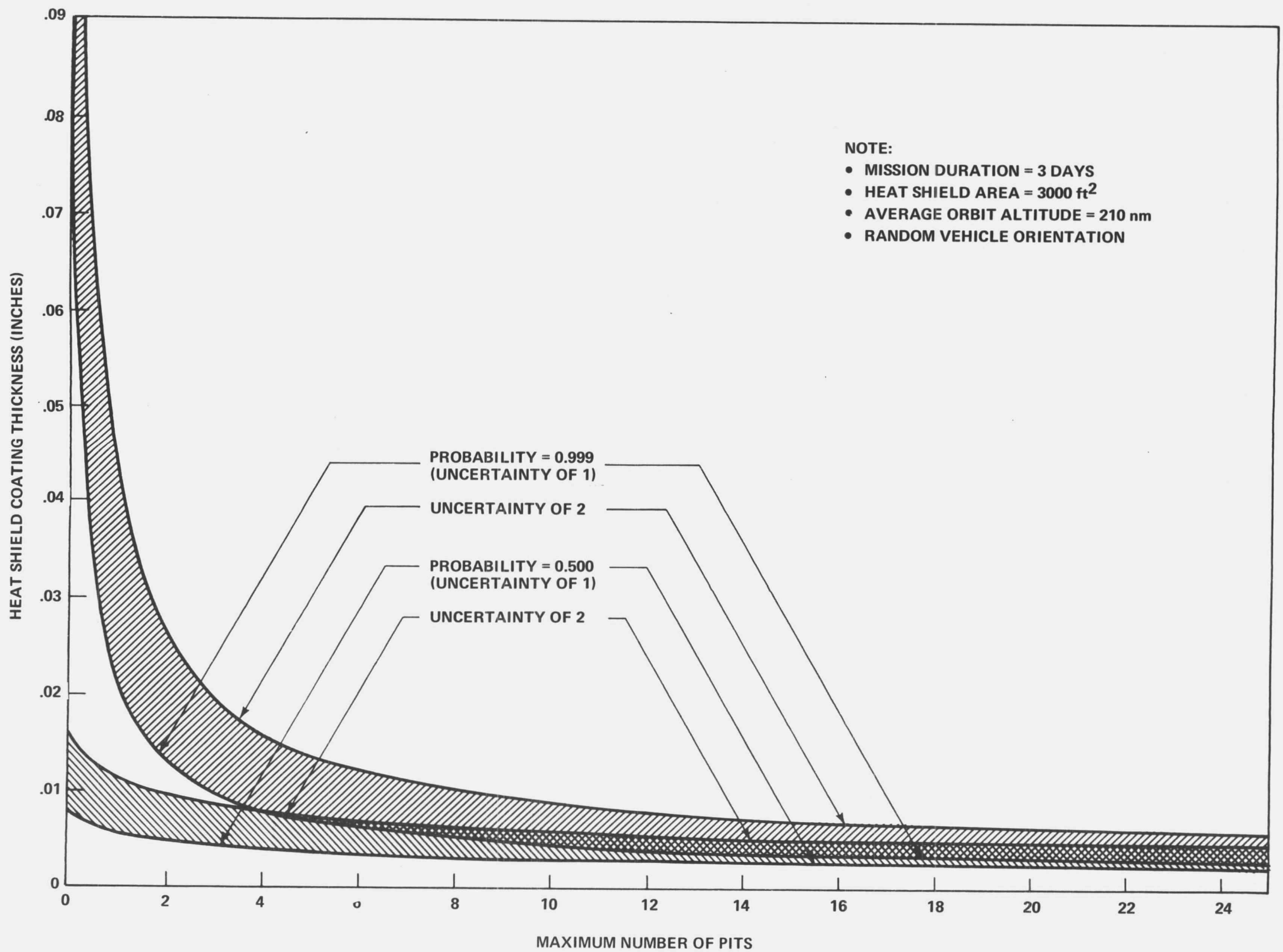

FIGURE 3 - HEAT SHIELD COATING PITTING RATES FOR PROBABILITIES OF 0.999 AND 0.500 AND UNCERTAINTIES OF 1 AND 2

in designing against the meteoroid environment with a probability of 0.5 than with a probability of 0.999). The values of 0.5 and 0.999 were chosen as representing extremes encountered in meteoroid shielding design. For each of the two probability values the effect of an uncertainty of 2 in thickness is shown. (An uncertainty of 1 infers that no uncertainty exists in theoretical approach used in this memorandum). Figure 4 shows the same variations as in Figure 3 only for larger values of n and includes intermediate values of probability.

Due to the asymptotic character of the curves (see Figure 3), an uncertainty of 2 in thickness will allow only a fraction of a pit to occur if the shield is designed for zero pits. However, when many pits are concerned, an uncertainty of 2 can create large differences in results. For heat shield coatings of 0.003 to 0.004 inches and uncertainties of 1 and 2, the number of expected pits for probabilities of 0.5 and 0.999 are shown in Table 1. It is seen that the results corresponding to an uncertainty of 2 are 4 to 8 times as large as those for an uncertainty of 1. Therefore, the ability to predict heat shield coating pitting rates is very sensitive to the degree of uncertainty involved.

TABLE 1 - Heat Shield Coating Pitting Rates

Probability	Number of Pits			
	Uncertainty of 1		Uncertainty of 2	
	Coating Thickness			
	0.004 in.	0.003 in.	0.004 in.	0.003 in.
0.999	12	22	51	100
0.500	4	10	31	77

5.0 CUMULATIVE DAMAGED COATING AREA

An estimate of the total pitted area resulting from meteoroid impacts that penetrate the coating can be made. Assuming that a meteoroid impact makes a hemispherical crater with a coating-surface diameter equal to twice the hole depth, the damaged surface area can be determined using Figures 3 and 4 and the equation.

$$\text{Cumulative Damaged Area} = \pi \sum_{i=1}^{n} t_i^2 \quad .$$

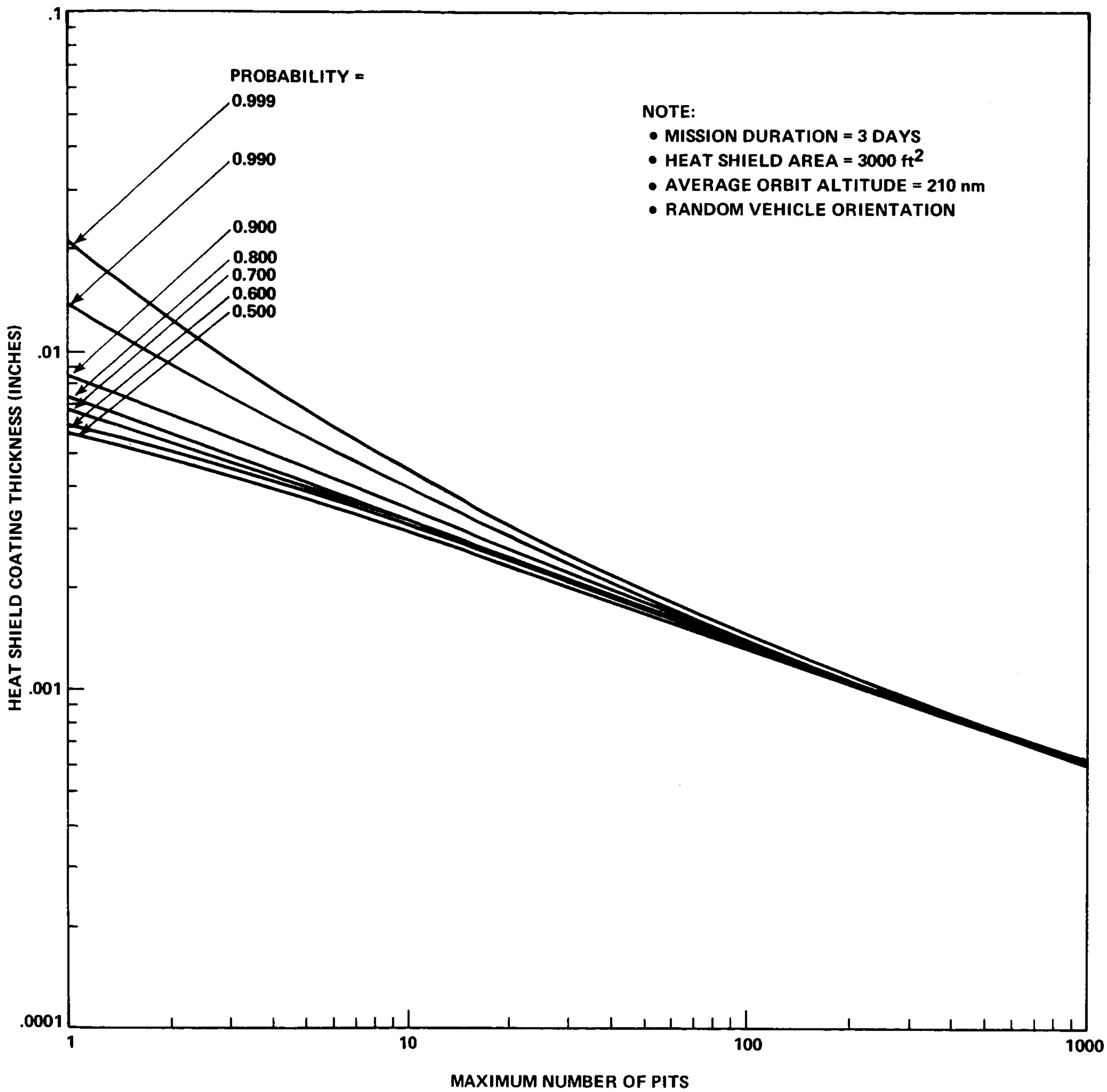

FIGURE 4 - HEAT SHIELD COATING PITTING RATES

The letter t refers here to the depth of penetration and n corresponds to the number of pits that are expected. However, these results will be low since the hardness of the shield varies from a very high value at the coating surface to a much lower value for the columbium base metal. Larger particles will therefore penetrate deeper than that indicated by Figures 3 and 4. The results are adjusted accordingly by assuming the properties of the total composite heat shield (see Section 6.0) to apply at penetration depths greater than twice the coating thickness.

Assuming a coating thickness of 0.003 inches, Table 2 lists the P=0.999 cumulative damaged coating areas with respect to the number of pits and uncertainties of one and two.

TABLE 2 - P=0.999 Cumulative Damaged Coating Areas for Coating Thickness of 0.003 in.

Uncertainty	Number of Pits	Maximum Damaged Area, in.^{2}
1	22	4.4×10^{-3}
2	100	22.0×10^{-3}

6.0 PUNCTURE OF THE TOTAL HEAT SHIELD

To assess the probability of the total columbium heat shield cross section (Figure 2) being punctured, the composite heat shield is idealized as one material of equal thickness and uniform penetration resistance. A composite equivalent Brinell Hardness Number of 330 and a density of 9.3 g/cc are used together with a spall factor of 1.5.* The BHN of Cb-752 is estimated by assuming the relationship, Tensile Strength = 515 BHN (Reference 8). The BHNs of two 0.0034 inch coatings are then "weighted" with the estimated BHN of a 0.020 inch CB-752 base metal to obtain the composite BHN of approximately 330.

The expected number of punctures for various probabilities and total heat shield thickness are plotted in Figures 5 and 6 and are generally summarized in Table 3. Notice that a total heat shield thickness of 0.026 inches will not satisfy a criterion of greater than 0.9 that no punctures will occur.

*Spall is ejecta emitted from the rear face of a structure of finite thickness due to high speed particle impact. A spall factor relates the semi-infinite penetration depth to an equivalent thin-sheet thickness of equal penetration resistance.

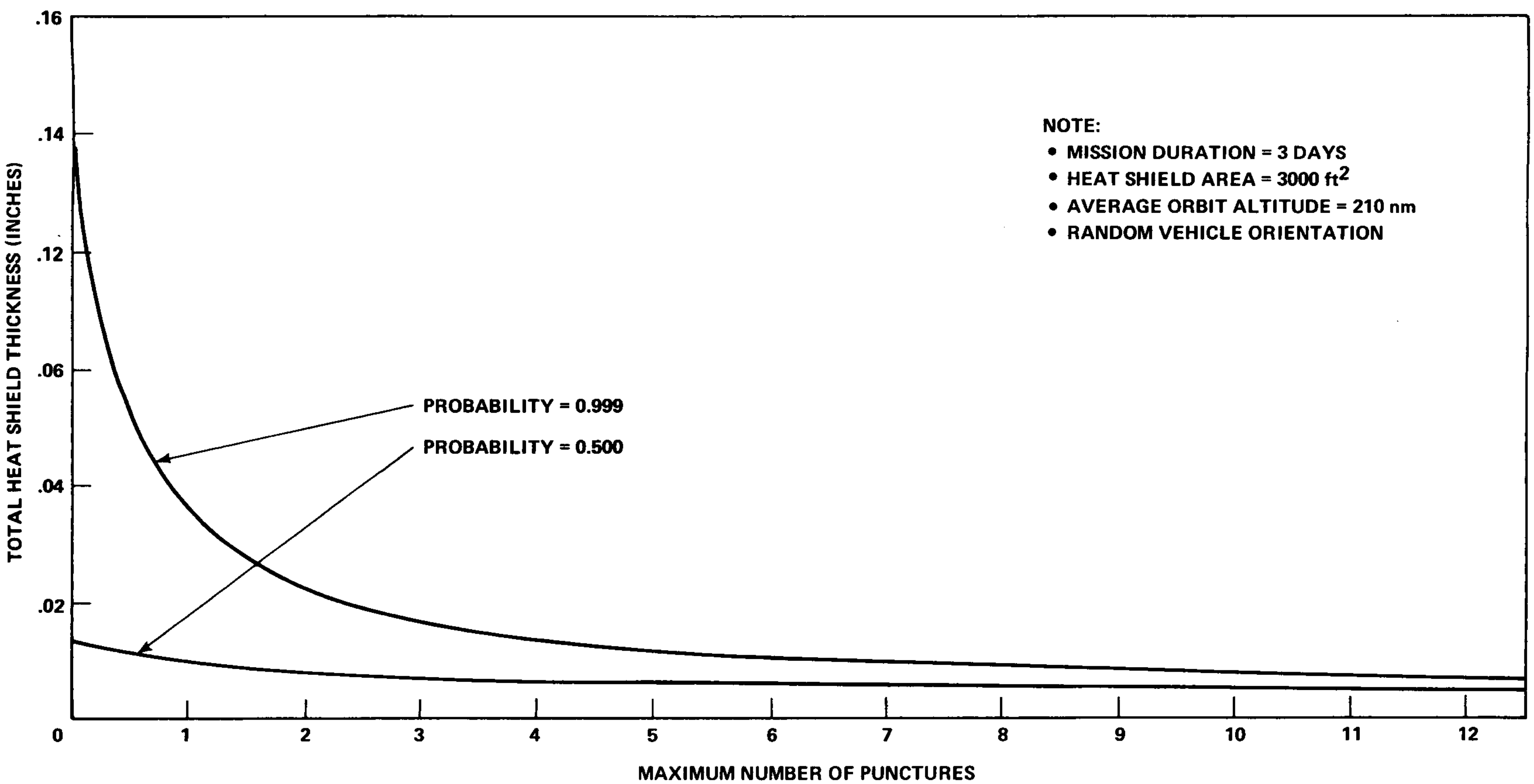

FIGURE 5 - TOTAL HEAT SHIELD THICKNESS PUNCTURE RATE FOR PROBABILITIES OF 0.999 AND 0.500

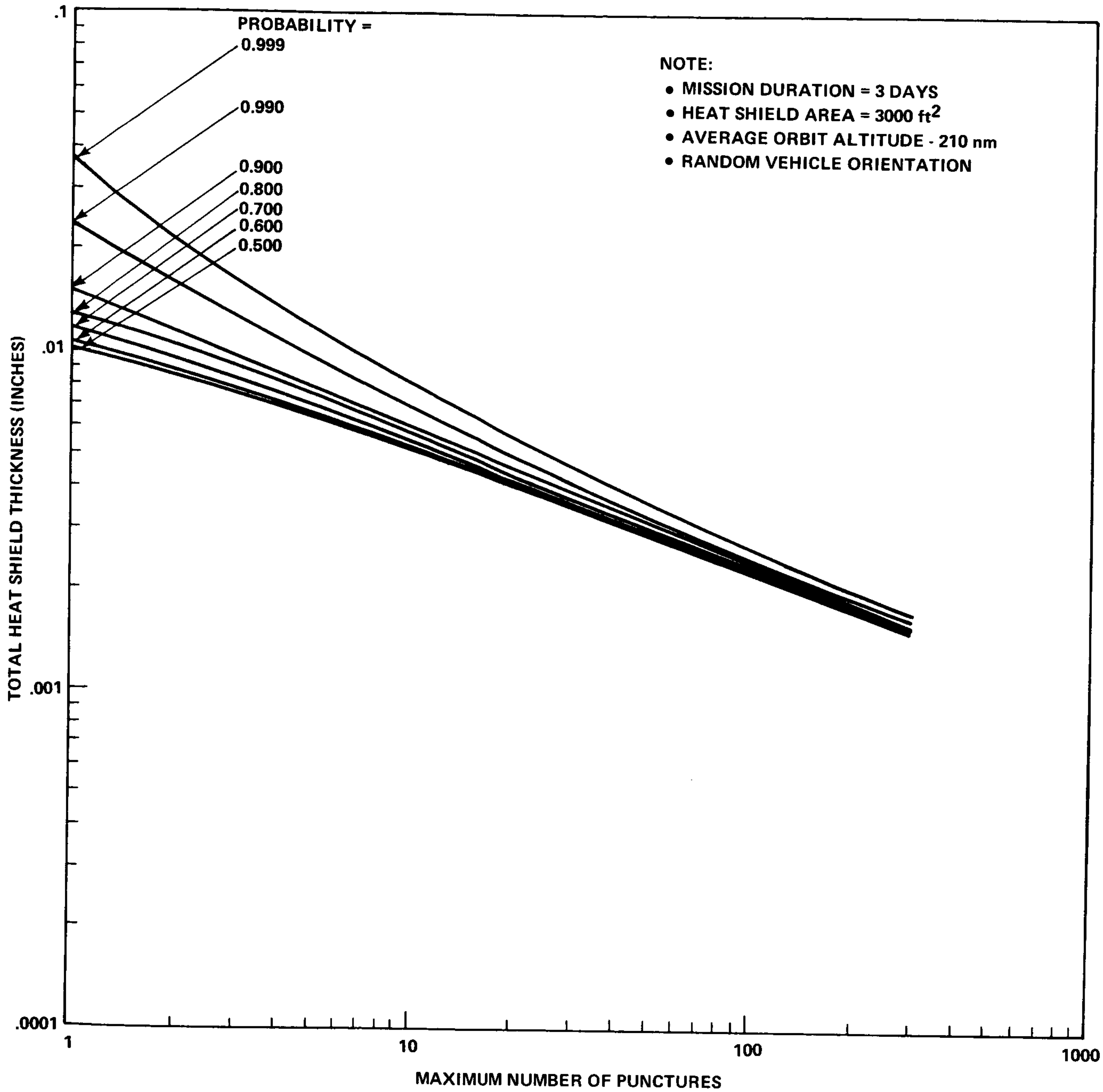

FIGURE 6 - TOTAL HEAT SHIELD THICKNESS PUNCTURE RATE

TABLE 3 - Required Total Heat Shield Thickness (inches)

Number of Punctures	Probability				
	0.999	0.99	0.9	0.8	0.7
0	0.1367	0.0605	0.0269	0.0204	0.0170
1	0.0356	0.0243	0.0149	0.0128	0.0115
2	0.0233	0.0161	0.0115	0.0103	0.0095
3	0.0165	0.0128	0.0098	0.0089	0.0083

7.0 SPACE SHUTTLE HEAT SHIELD HAZARDS AND METEOROID DESIGN CRITERIA IMPLICATIONS

7.1 Hazards

Two heat shield hazards can occur due to meteoroid impact:

- the loss of heat shield structural strength due to substrate oxidation or penetration, and
- risk to internal Space Shuttle systems due to total heat shield puncture resulting in hyper-velocity particle fragmentation and subsequent heat leakage.

The first hazard has been investigated by several companies. McDonnell Douglas Astronautics Company (Reference 9) experimentally studied the effect of local coating damage on the structural integrity of Cb-752 coated with Sylvania R512E System. Small test specimens with damages previously induced by mechanically removing coating areas of 30 to 375 mils in diameter were exposed to a maximum temperature of 2400°F in a high stress and a low pressure static oxidation environment. Results show that the damage sites are not structural weak points and that locally damaged specimens can structurally resist tens of static heating cycles before failure. Sylvania Electric Products (Reference 10) also conducted similar tests on artifically defected coupons of coated columbium alloy D-43. The defects consisted of small holes 17 to 32 mils in diameter, drilled completely through the coated coupons. The specimens were also exposed to a static oxidation environment of low pressure at 2500°F. After 10 simulated reentry cycles, a yellow columbium oxide was formed around the holes but the holes had not been appreciably enlarged.

These test results suggest that small local coating damage and even small holes through the total heat shield cross section may not jeopardize the structural integrity of the Space Shuttle heat shield. However, this may not be the case since these results were obtained from static furnace test environments. To adequately assess the heat shield meteoroid hazard and establish acceptable values of damaged coating surface areas for Space Shuttle designs, more realistic aerothermal test simulations are needed.

The static tests indicate that damaged areas can be visually identified due to the yellow discoloration effect produced by columbium oxidation. This could facilitate post flight inspection and refurbishment operations.

The second hazard resulting from total heat shield puncture has not been investigated. A thorough understanding of this problem is needed to establish a basis for criteria formulation. In particular, can meteoroid punctures through the entire heat shield cross section be allowed or not? Criteria may vary locally depending on what is underneath that part of the heat shield.

7.2 Meteoroid Design Criteria Implications

Weight Penalties

Meteoroid protection weight penalties are highly sensitive to the selection of design criteria and can be inordinately large when considered in terms of Space Shuttle payload capability. Table 4 lists 3-day-mission weight penalties for criteria of no punctures P(0) and one puncture or less occurring P(0,1), based on the current heat shield weight estimate by McDonnell Douglas of 1.4 lbs/ft^2 (Reference 2) which does not consider the effects of the meteoroid environment. It is seen that if a no-puncture probability of 0.999 is adopted (typical of Apollo), the concept of metallic radiative heat shield design does not appear very attractive, since 62.4 percent of a 25000 lb Space Shuttle payload capability is sacrificed. However, if one puncture is allowed, the heat shield weights decrease significantly to values approximately equal to McDonnell Douglas' current estimate.

TABLE 4 - Space Shuttle Heat Shield Meteoroid Design Criteria/Weight Penalties

	Designed for Meteoroid Environment				Not Designed For Meteoroid Environment (McDonnell Douglas)
	0.999		0.99		
	P(0)	P(0,1)	P(0)	P(0,1)	
Unit Weight of Heat Shield (lbs/ft^2)	6.6	1.7	2.8	1.1	1.4
Weight Increase For 3000 ft^2 of Shield (lbs)	15,600	900	4,200	0	0
Weight Increase as Percentage of a 25000 lb Payload	62.4	3.6	16.8	0	0

Mission Duration and Frequency of Post Flight Inspection and Refurbishment (I/R) Operations

Space Shuttle heat shield weights are a function of accumulated flight time between ground operations required for the detection and possible repair of meteoroid damage. Whether the flight time is accumulated by flying one long mission or a sequence of short consecutive missions of varying durations makes no difference. Therefore, in addition to the usual tradeoff existing between meteoroid shielding payload penalties and allowable mission durations, a further tradeoff exists in Space Shuttle design. Namely, is it more economical to fly one mission or a number of missions between I/R operations?

Meteoroid shielding payload penalty relationships with 1) mission durations, and 2) I/R operations are shown in Figures 7 and 8 respectively, for the case of total heat shield puncture. These figures are based on Table 4 and the equation (from Equation 6A)

$$\text{Heat Shield Weight} \propto (\text{Total Flight Time})^{0.353}.$$

For the case of heat shield coating pitting, the relationships depend on acceptable values of damaged coating areas which remain to be established (see page 8).

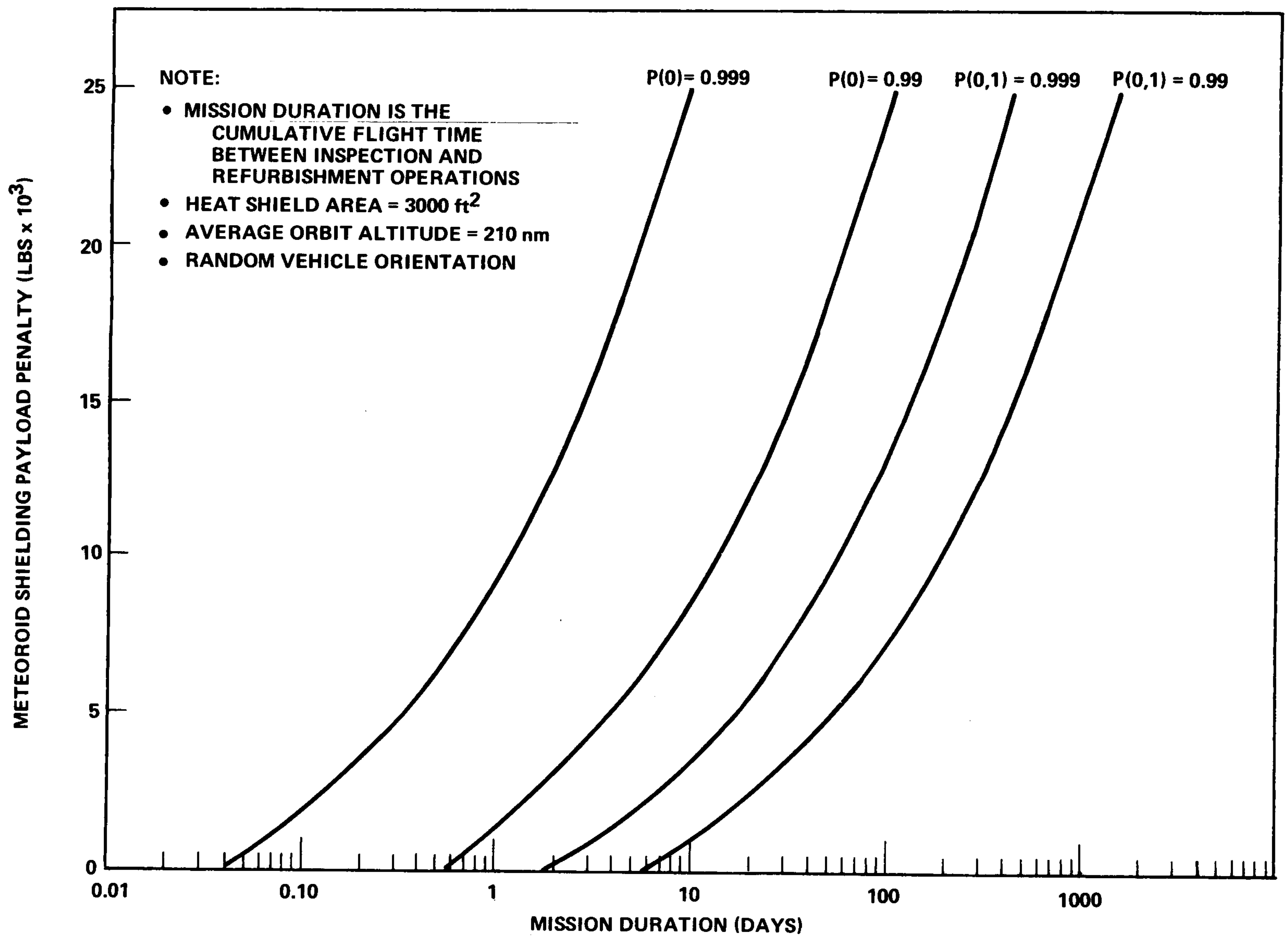

FIGURE 7 - METEOROID SHIELDING PAYLOAD PENALTY VERSUS MISSION DURATION FOR HEAT SHIELD PUNCTURE

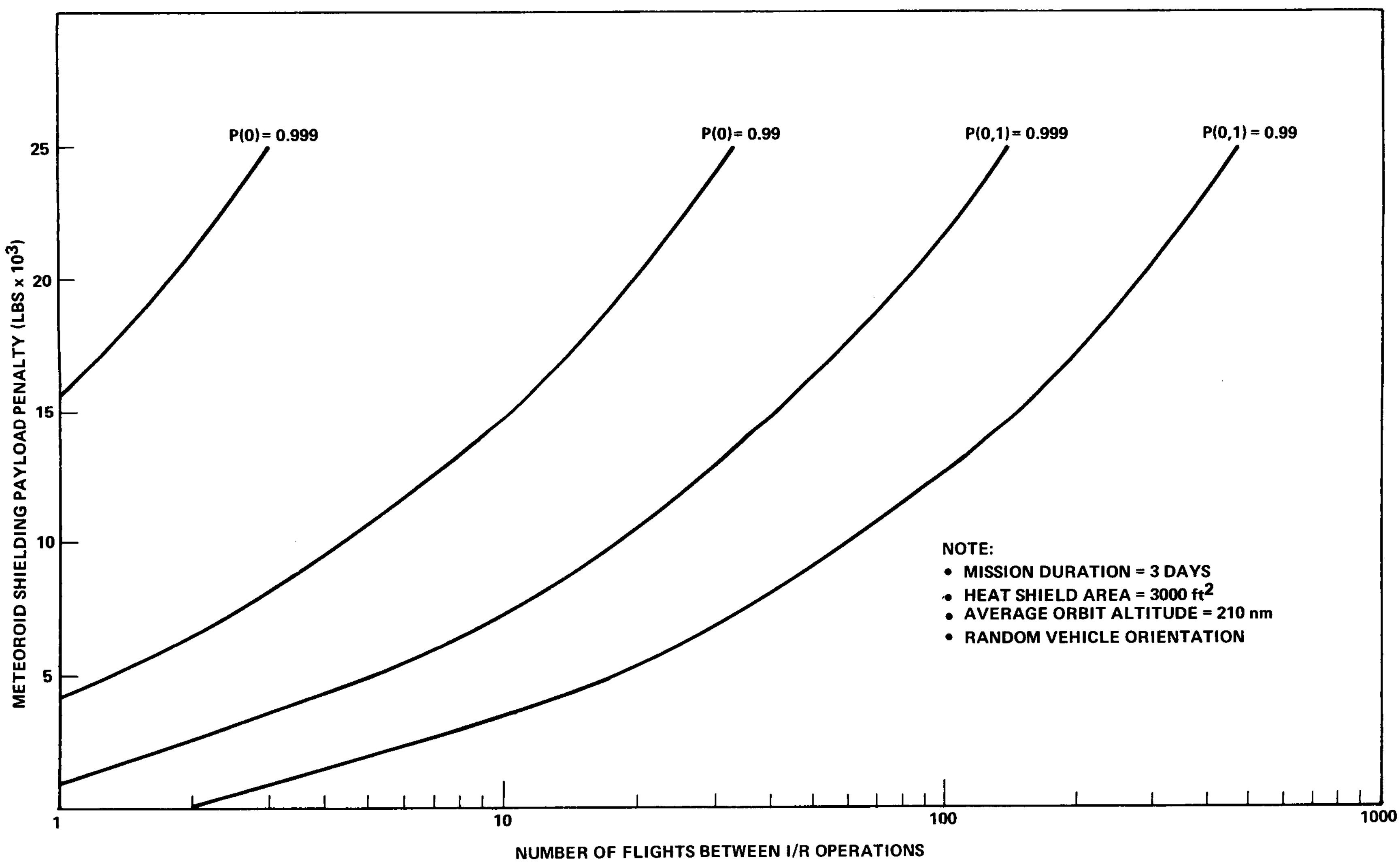

FIGURE 8 - METEOROID SHIELDING PAYLOAD PENALTY VERSUS THE FREQUENCY OF INSPECTION AND REFURBISHMENT (I/R) OPERATIONS FOR HEAT SHIELD PUNCTURE

Figure 8 depicts the meteoroid shielding/IR operations trades which are involved for consecutive 3-day missions. Payload penalty is plotted against the number of flights between I/R operations for various meteoroid design criteria. It is apparent that:

(1) payload can be traded for I/R operations (or mission durations),

(2) reliability against meteoroid damage can be traded for I/R operations (or mission durations), and

(3) payload can be traded for reliability against meteoroid damage.

The tradeoff between payload capability and I/R operations is particularly significant in that it is severe and affects program cost. For example, to maximize reusability the number of flights between I/R operations must also be maximized. But, this in turn substantially reduces payload capability necessitating more flights to deliver a desired payload into space. Dollars are saved by reducing I/R operations, but they are spent since more flights are required.

The number of flights between I/R operations can also be maximized by relaxing the reliability against meteoroid damage. In general, relaxation of a no-puncture probability of 0.999 to 0.99 will increase the number of flights between I/R operations (or mission durations) by an order of magnitude. In addition, if one puncture is allowed, a further order-of-magnitude increase will occur. Space Shuttle meteoroid design criteria remain to be established.

The payload penalty can be reduced by relaxing the reliability against meteoroid damage. For mission durations between approximately 3 to 10 days, relaxation of a no-puncture probability of 0.999 to 0.99 will decrease the payload penalty by a factor of $\approx 2/3$. In addition, if one puncture is allowed, no significant payload penalties will occur.

8.0 CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

General

- If the Space Shuttle were to fly only in a heat-shield-down orientation (facing the

- earth) very little additional meteoroid protection, if any, would be required on the windward surfaces.

- The total flight time between inspection and repair operations for a sequence of consecutive missions of varying durations, equals the allowable mission duration for a single flight.

Meteoroid Pitting of Heat Shield Coating

- Less than 100 pits per mission should occur in the heat shield coating with a more likely number of about 20. The corresponding damaged coating surface areas are 0.022 in^2 and 0.004 in^2 respectively.

- The prediction of the number of pits is very sensitive to the uncertainty involved.

- Acceptable values of damaged coating surface areas for Space Shuttle design remain to be established. Post flight inspection and repair may be required after each flight.

- Tests indicate that damaged coating areas due to meteoroid impact can be visually identified due to the yellow discoloration effect produced by columbium oxidation during atmospheric reentry. This could facilitate post flight inspection and refurbishment operations.

Meteoroid Puncture of Total Heat Shield

- Radiative heat shields currently designed by minimum gage estimates and requirements for heating and aerodynamic loading (see Figure 2) will not satisfy a meteoroid design probability of greater than 0.9 that no punctures will occur.

- If a no-puncture probability of 0.999 is adopted (typical of Apollo), the concept of a radiative metallic heat shield does not appear very attractive due to large weight penalties.

- For mission durations of approximately 3 to 10 days, relaxation of a no-puncture probability of 0.999 to 0.99 will decrease meteoroid payload penalties by $\approx 2/3$. In addition, if one puncture is allowed, no significant payload penalties will occur.

- Sacrifice of payload capability will increase the number of flights between post flight inspection and refurbishment (I/R) operations (or increase mission durations). However, this tradeoff is severe and affects program cost.

- Relaxation of a no-puncture design criterion of 0.999 to 0.99 will increase the number of flights between I/R operations (or mission durations) by an order of magnitude. In addition, if a puncture can be accepted, a further order-of-magnitude increase will occur.

8.2 RECOMMENDATIONS

- To adequately assess the risk of critical heat shield meteoroid damage, laboratory testing should be performed which includes the effects of high speed hot-gas impingement similar, to the reentry environment, against test specimens.

- An investigation of potential hazards associated with total heat shield meteoroid puncture should be undertaken to establish whether or not punctures can be accepted in Space Shuttle design. These hazards involve the risk to internal systems due to hypervelocity particle fragmentation and subsequent heat leakage.

- Hypervelocity impact testing should be performed to aid in determining the meteoroid penetration characteristics of typical metallic radiative heat shields.

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APPENDIX A

ANALYSIS

Nomenclature:

N = Number of impacts per square foot per day exceeding a particle mass m

m = Meteoroid mass, grams

ρ_m = Unit weight of impacting particle, g/cc

ρ_t = Unit weight of target material; 5.85 g/cc for the coating and 9.3 g/cc for the entire heat shield.*

V_m = Impact velocity of impacting projectile, km/sec

A = Exposed area to meteoroid environment, ft^2

T = Duration of Space Shuttle in the meteoroid environment, days.

t = Coating thickness, inches

d = Depth of penetration, inches

d_m = Diameter of impacting projectile, cm

H_t = Brinell Hardness Number; 780 → 1050 for the coating and 330 for the total heat shield, kg/mm^2

n = Number of penetrations

λ = Expected events = NFAT

$P(0,1,2...n)$ = Probability of n or less events occurring

F = Shielding Factor

R = Radius of shielding body, km

H = Altitude above shielding body, km

*Unit weight of coating obtained from reference cited in footnote on page 2 of memorandum.

Assumptions:

1. The heat shield coating is between 0.003 and 0.004 inches thick.

2. The Apollo cislunar meteoroid environment cited in NEPSAP applies (Reference 4).

$$\log N = -\log m - 9.695$$
$$\rho_m = 0.5 \text{ g/cc} \qquad \text{(A-1)}$$
$$V_{avg} = 30 \text{ km/sec}$$

3. The North American-Rockwell penetration equation applies (Reference 5).

$$d = 0.543\, d_m^{1.06} \rho_m^{0.5} V_m^{0.67} \rho_t^{-0.167} H_t^{-0.25} \qquad \text{(A-2)}$$

4. Impacting meteoroid particles are spherical in shape.

5. The theory for penetration into a semi-infinite body is used since the coating is 1/5 to 1/9 the thickness of the total heat shield.

Equations (A-1) and (A-2) can be combined to relate to the mass of the design meteoroid and the required coating thickness with probability as follows:

The probability of n penetrations or less occurring can be expressed using the Poisson distribution as

$$P(0,1,2\cdots n) = \sum_{n=0}^{n} \frac{e^{-\lambda}\lambda^{n}}{n!}$$

The average number of expected events n can be expressed as

$$\lambda = NFAT \qquad \text{(A-3)}$$

Using equation (A-1), the meteoroid flux can be written as

$$m = \frac{2.02 \times 10^{-10} FAT}{\lambda} \qquad (A-4)$$

Expressing the meteoroid diameter in terms of mass

$$d_m = \left(\frac{6m}{\pi \rho_m} \right)^{1/3} \qquad (A-5)$$

Substituting equations (A-5) and (A-6) into (A-2) and equating depth of penetration to coating thickness, the required thickness to prevent coating penetration can finally be written as

$$t = 2.59 \times 10^{-4} \left(\frac{FAT}{\lambda} \right)^{0.353} \rho_m^{\ 0.147} V_m^{\ 0.67} \rho_t^{\ -0.167} H_t^{\ -0.25} \qquad (A-6)$$

The values of λ associated with various probabilities of n or less punctures occurring can be determined as follows:

- For $n \leq 15$, the cumulative Poisson distribution is listed in most statistics textbooks (Reference 11).

- For $15<n<50$, λ can be approximated by the equation (Reference 12, Equation 26.4.14, Page 941).

$$\lambda = \left\{ x_1 \left[\frac{1}{9(n+1)} \right]^{1/2} - \frac{1}{9(n+1)} + 1 \right\}^3 (n+1)$$

For n>50, λ can be approximated by the equation (Reference 12, Equation 26.4.13, Page 941)

$$\lambda = \frac{1}{4}\left(\sqrt{4n + 3} + x_1\right)^2$$

Values of x_1 for various probabilities are (Reference 12, Table 26.5)

P = 0.999	x_1 = -3.09023
P = 0.99	x_1 = -2.32635
P = 0.9	x_1 = -1.28155
P = 0.8	x_1 = -0.84162
P = 0.7	x_1 = -0.52440
P = 0.6	x_1 = -0.25335
P = 0.5	x_1 = -0

The shield factor F is determined by (Reference 13)

$$F = \frac{1 + \cos \theta}{2}$$

where

$$\sin \theta = \frac{R}{R + H}$$

For a Space Shuttle orbiting the earth at an average altitude of 210 nm or 388 km, the shielding factor is

$$F = 0.669$$

APPENDIX B

Correlation of Theory with In-Flight Meteoroid Data

Satellite Data

The perforation rates of thin sheets of stainless steel (Explorer XIII), beryllium-copper (Explorer XVI), and aluminum (Pegasus) have been measured directly in the near-earth meteoroid environment. The Explorer results are analyzed in detail in Reference 14, and the Pegasus points, in Reference 15.

The Explorer points are regarded with greater confidence than the Pegasus points for several reasons. First, the Explorer detectors consisted of pressurized cans where perforation of the exposed wall was recorded as a pressure drop and provided an unambiguous record of impact. On the other hand, the Pegasus detectors consisted of a capacitor device where the outer aluminum sheet was laid directly onto a dielectric layer separating the capacitor plates. Perforation was detected by a short in the capacitor. The detectors were thought to give spurious readings when subjected to extremes of electron radiation. Second, the threshold perforation of the aluminum sheet was probably affected by the dielectric layer and other backing materials. A heavier projectile was probably necessary to give a recorded "hit" on the Pegasus detector than would have been required using a single thin sheet of the same thickness. A calibration program for the Pegasus detectors was carried out, but the results are inconclusive (Reference 16).

Data Presentation

Alvarez has obtained an estimate of a conversion equation relating Pegasus thicknesses to equivalent Explorer thicknesses (Reference 14). He obtains

$$t(\text{Peg}) = 0.82\ t(\text{Exp}). \tag{B-1}$$

That is, the 200-micron aluminum Pegasus detector is equivalent to a 244-micron stainless steel thin sheet. This equation was determined from the requirement that the data fit a parabola and is therefore a theoretical prediction. It has been used to adjust the Pegasus data as shown in Figure B-1. Alvarez has correlated the results for the three materials in Reference 14 (page 85) and has obtained the following thin-sheet perforation rate equation

$$\log_{10}N = -5.9657 + 1.3638\ \log_{10}t - 0.6831\ \log^2_{10}t, \tag{B-2}$$

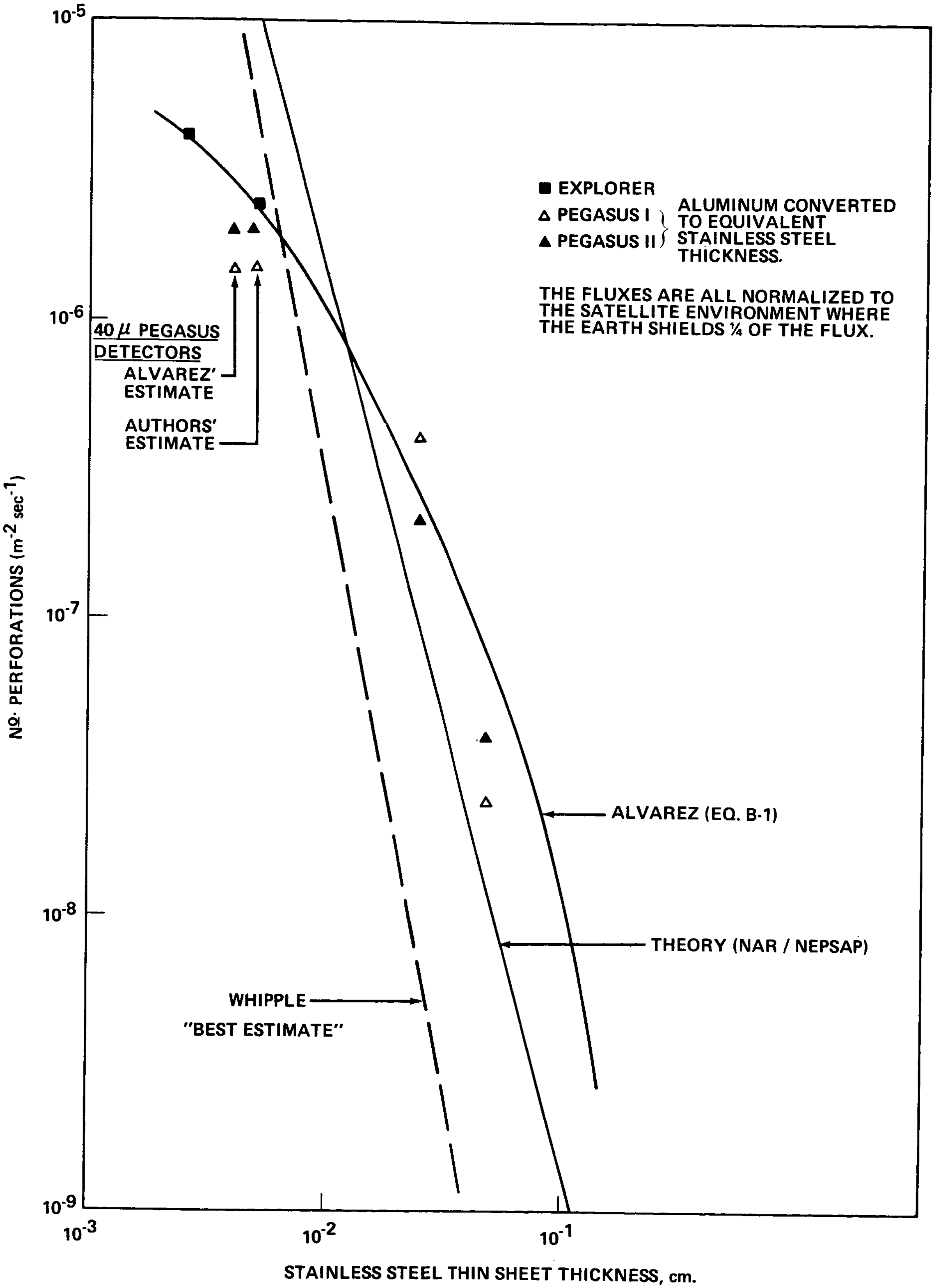

FIGURE B-1 - STAINLESS STEEL THIN SHEET PERFORATION FLUX where N is the perforation rate of stainless steel in number per m^2 per sec, and t is the stainless steel thin sheet equivalent thickness in microns (μ). This equation is considered valid by Alvarez for $10\mu < t < 8.4 \times 10^3 \mu$, and is shown plotted in Figure B-1 together with the satellite data.

The authors have also made an estimate of the material thickness conversion relation between the Pegasus and Explorer detectors. This estimate involves accounting for both the detector material and configuration differences. Using the North American Rockwell (NAR) equation (A-2), material differences between aluminum and stainless steel were accounted for by the equation

$$\frac{t_{ss}\ (\text{Peg})}{t_{Al}\ (\text{Peg})} = \left(\frac{\rho_{Al}}{\rho_{ss}}\right)^{0.167} \left(\frac{H_{Al}}{H_{ss}}\right)^{0.25},$$

where H is the Brinell Hardness Number and ρ is the density of the target. BHN values were taken to be 80 for the 40μ 1100-0 detector, and 150 for the 200μ and 400μ 2024 T-3 detectors.

Since the Pegasus detectors do not record a "hit" until the 12μ mylar dielectric layer has been perforated, this layer must be added to the thickness of aluminum to arrive at the combined thickness of material presented by the detector to the meteoroid environment (see Reference 15 for a diagram of the detector). The aluminum equivalent thickness of the mylar layer is 10μ. This layer makes a significant change to the 40μ detector only.

Configuration differences between detectors were accounted for by a spall factor (defined on page 6 of the memorandum). Perforation of the Pegasus detector more closely resembles penetration into a semi-infinite target, while perforation of the Explorer detector corresponds to thin-sheet perforation. To convert from one to the other, a spall factor of 1.5 was used.

Considering both detector material and configuration differences, the authors determined the following material thickness conversion equations:

$t(\text{Peg}) = 0.87t\ (\text{Exp})$ for the 200μ and 400μ detectors, and

$t(\text{Peg}) = 0.99t\ (\text{Exp})$ for the 40μ detector.

The conversion equation for the 200 and 400μ detectors compares well with Equation (B-1). The data points shown on Figure B-1 for these detectors may therefore be taken to correspond to either conversion method to within 5%. However, the estimate for the 40μ detector is shown displaced to the right of the Alvarez estimate and now more closely agrees with the other data.

Correlation

The correlation between theory and in-flight meteoroid data is best shown by plotting on Figure B-1 the stainless-steel-sheet flux rate obtained using the theoretical method described in Appendix A. To convert from the NAR penetration equation, a spall factor of 1.5 was used for the coating calculations.

Using the values $\rho_m = 0.5$ gm/cm^3, $v_m = 30$ km/sec, $\rho_t = 8.3$ gm/cm^3 (stainless steel), and $H_t = 200$ (stainless steel), the number of perforations per m^2 per sec in a thin stainless steel sheet of thickness t(cm) is

$$N = \frac{1.8 \times 10^{-12}}{t^3} \text{ m}^{-2} \text{ sec}^{-1}.$$

Allowing for an earth shielding factor of 3/4, (the conditions during the satellite experiments), the NAR/NEPSAP equation reduces to

$$N = \frac{1.35 \times 10^{-12}}{t^3} \text{ m}^{-2} \text{ sec}^{-1}. \qquad \text{(B-3)}$$

Equation (B-3) is plotted on Figure B-1 together with the Whipple curve of "Best Estimate" (Reference 17), which is often used for comparison purposes.

Discussion

The agreement between the satellite data and the theoretical prediction (NAR/NEPSAP) is very good considering the many uncertainties. Probably the most serious uncertainty in the satellite data is that of converting the Pegasus aluminum data to the equivalent Explorer data as explained above. In addition, the use of the NAR equation is in doubt because it was developed for penetration into semi-infinite targets and for relatively low velocities which are not representative of meteoroid impact, as discussed in Section 3.0 of the memorandum.

The good correlation between the satellite data and the theoretical approach used in this study supports the belief that a significant hazard is presented by the meteoroid environment to the heat shield.